# EXERCISE 4

# NUMERICAL DATING

**Supplies Needed**

• calculator

## PURPOSE

Numerical dating assigns numbers to the events and intervals of the Earth's history. Dating is often the most crucial tool in studies of active tectonics. Assessment of earthquake hazard in the future is based on information about the timing and rates of activity in the past. The purpose of this exercise is to familiarize you with the basic principles of numerical dating. You will apply these principles and use numerical dates throughout the rest of this book.

## INTRODUCTION

A variety of techniques are now available to geologists studying active tectonics. In any given research situation, the technique used depends mainly on the type of material present and its suspected age. Figure 4.1 illustrates the effective age ranges for three of the most reliable dating techniques for material formed in the Quaternary (the last 1.65 million years).

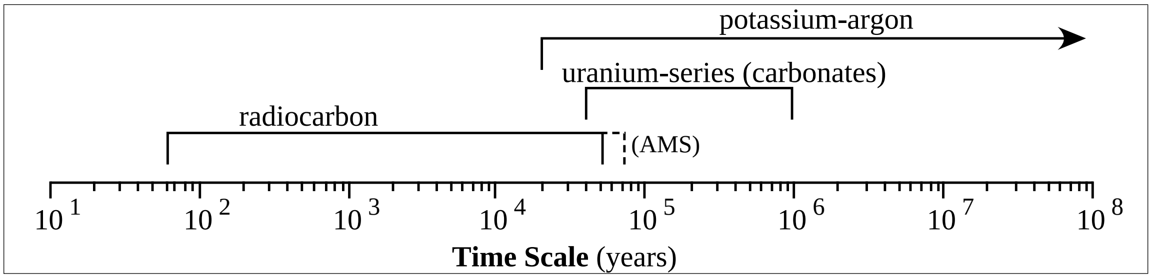


Figure 4.1. The three most-used techniques for dating material formed during the Quaternary (the last 1.65 million years) and the age ranges over which they are useful. See the text for descriptions of the types of material that can be analyzed using these methods.

## Numerical Dating

The radiocarbon technique (also known as $^{14}C$ dating) is suitable for most organic material, including charcoal, wood, plant fiber, bone, and shell. AMS (Accelerator Mass Spectrometry) is an alternative radiocarbon technique that is more precise and requires smaller samples than does conventional radiocarbon analysis. Uranium-series dating includes several different techniques based on the decay from either $^{235}U$ or $^{238}U$. The uranium-series technique that is most useful in geomorphology is used to determine the ages of corals and shells. Potassium-argon dating, and the more refined argon-argon technique, are suitable for dating igneous rocks and volcanic ashes. Other dating techniques useful for Quaternary material include amino-acid racemization, fission-track dating, obsidian hydration, thermoluminescence, tephrachronology, and a variety of new techniques based on cosmogenic isotopes (created by cosmic rays).

## RADIOACTIVE DECAY

Most of the dating techniques listed here, including all three of the most-used methods shown in Figure 4.1, are based on measurements of radioactive *isotopes*. Each individual element in the Periodic Table has a fixed number of protons, but the number of neutrons may vary. Isotopes are forms of the same element with different numbers of neutrons and therefore different atomic mass numbers (the number of protons plus neutrons). For example, the element carbon has three different isotopes – all with six protons, but one with six neutrons ($^{12}C$), one with seven neutrons ($^{13}C$), and one with eight neutrons ($^{14}C$).

Carbon has two isotopes that are stable ($^{12}C$ and $^{13}C$) and one isotope that is unstable ($^{14}C$). The $^{14}C$ isotope spontaneously decays from its original form (called the *parent isotope)* into another form entirely (called the *daughter product).* The $^{14}C$ parent decays into $^{14}N$, which is its stable and non-radioactive daughter product. Another

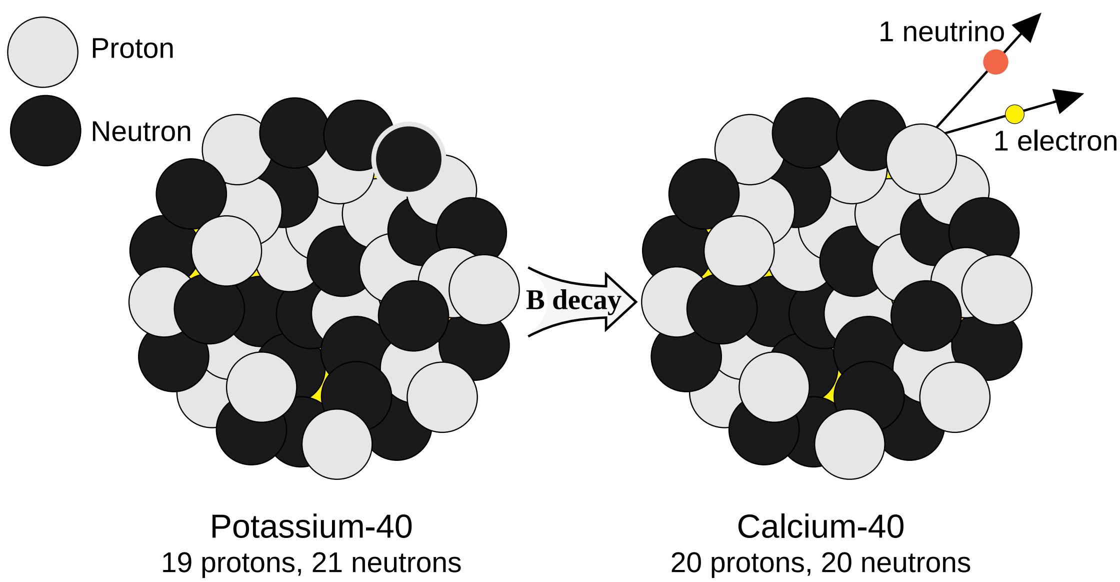


Figure 4.2. Illustration of radioactive decay. In this example, a $^{40}K$ is transformed into a $^{40}Ca$ when a neutron decays into a proton, emitting a neutrino and an electron.

example useful to numerical dating is the $^{40}K$ parent isotope, which has two decay paths: into $^{40}Ar$ and $^{40}Ca$ (Figure 4.2). In a closed system (for example, in a sealed mineral crystal), the number of parent atoms steadily decreases over time, while the number of daughter atoms increases (Figure 4.3). The fact that makes most numerical dating possible is that the rate of radioactive decay for a given isotope is constant. This means, for example, that by measuring the rate at which $^{40}K$ decays in a laboratory today, we know the decay rate throughout geological time. Decay rate of a given isotope commonly is given in terms of *half-life*, which is the time it takes for exactly one-half of the parent atoms in a closed system to turn into daughter atoms. The ratio of parents to daughters is 1:1 after one half-life, 1:3 after two half-lives (3/4 daughters), 1:7 after three half-lives (7/8 daughters), etc. (Figure 4.3).

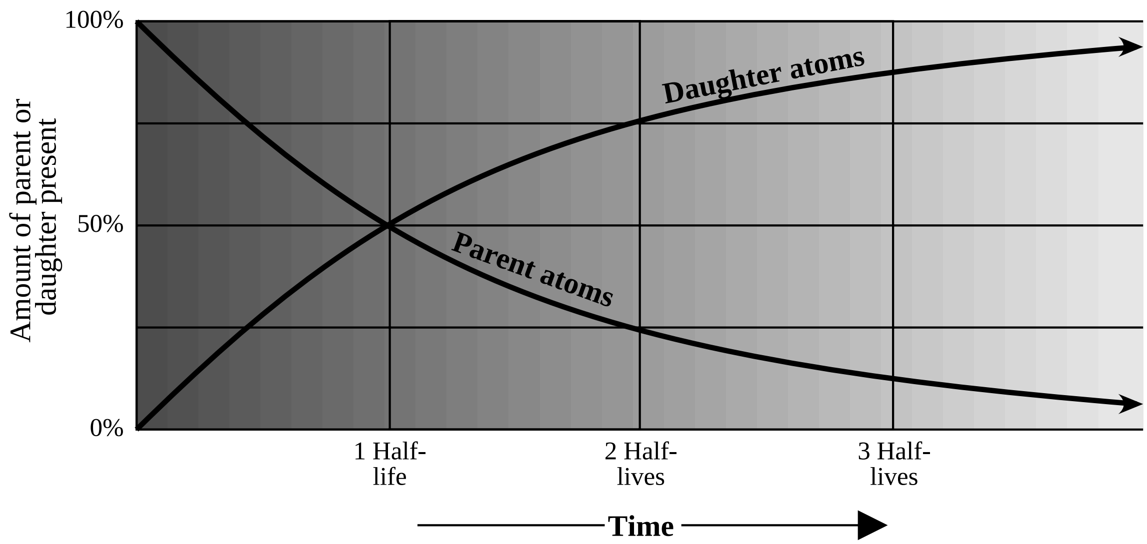


Figure 4.3. During radioactive decay, the number of parent isotopes declines, decreasing by a factor of two during each half-life. If the daughter product of the decay is stable, its abundance steadily increases.

Example 4.1.

As stated in the text, the element carbon consists of three different isotopes: $^{12}C$, $^{13}C$, and $^{14}C$ the Earth's atmosphere, the relative abundance of these three isotopes remains almost constant over time because the decay of radioactive $^{14}C$ is balanced by the creation of new $^{14}C$ by cosmic rays. All living organisms are in equilibrium with the atmosphere and have approximately the same ratio of the different carbon isotopes as the atmosphere so long as they are alive. The relative abundance of the three carbon isotopes is given below:

| | | |
|---|---|---|
| $^{12}C$ | 98.89% | 12 amu (atomic mass units) |
| $^{13}C$ | 1.11% | 13 amu (atomic mass units) |
| $^{14}C$ | <0.01% | 14 amu (atomic mass units) |

Also shown above is the atomic weight of each isotope, given in atomic mass units (amu). In fact, 1 amu is defined as 1/12 the atomic weight of $^{12}C$. Another way to see atomic weight is that 1 mol ($6.02 * 10^{23}$ atoms) of $^{12}C$ has a mass of precisely 12 grams. The

Periodic Table of the Elements lists an atomic weight of 12.011 amu for carbon, which is the average weight of the three isotopes. That value is calculated as follows:

$$\begin{aligned} 0.9889 * 12 \text{ amu} &= \quad 11.867 \text{ amu} \\ 0.0111 * 13 \text{ amu} &= + 0.144 \text{ amu} \\ 0.0000 * 14 \text{ amu} &= \underline{+ 0.000 \text{ amu}} \\ &= \quad 12.011 \text{ amu} \end{aligned}$$

The average weight is the sum of the abundance of each isotope times its atomic weight.

Geologists make use of the systematic decay of unstable isotopes by measuring the ratio of parent to daughter atoms sealed into certain minerals, rocks, and organic substances. These measurements reveal the amount of time since the sample became sealed, knowing the radioactive decay rate. Isotopes each have their own half-lives, ranging from seconds to billions of years. Because extremely little parent material remains after more than six or seven half-lives, geologists must select an isotope with a half-life appropriate to the age of the sample. Depending on the nature of the sample and the isotope, the age estimate may represent the time when the rock or mineral formed, the time of last metamorphism (due to intense heat and pressure), or the age of the Earth.

As illustrated in Figure 4.3, the number of parent atoms decreases over time in a closed system as a result of isotopic decay. If the daughter product is stable, the number of daughters increases proportionally to the decrease in parents. The following equation describes the change in the number of parents:

$$N = N_o e^{-kt} \tag{4.1}$$

where N is the number of parent atoms present at time t, $N_o$ is the number of parent atoms present at t=0, and k is the rate constant. In Equation 4.1, "e" is the inverse of the natural logarithm function ("ln" on most calculators). The rate constant (k) is related to the half-life as follows:

$$t_{1/2} = \frac{0.693}{k} \tag{4.2}$$

where $t_{1/2}$ is the half-life of the parent isotope.

Example 4.2.

Parent isotope A has a half-life of 37,000 years. If a sample that originally consisted of 100% isotope A now consists of 65% daughter product, how old is the sample? The answer to this problem is determined as follows:

The problem tells you that $t_{1/2}$ = 37,000 years. Using Equation 4.2, you can find k:

$$k = {}^{0.693}/t_{1/2} = 0.693/_{37,000 \text{ yrs}} = 0.000019 \text{ per year.}$$

Knowing the half-life, the original amount of parent isotope (100%) and the amount of parent isotope present now (100% – 65% = 35%), you can use Equation 4.1 to find the age of the sample:

$$35\% = 100\% * e^{-0.000019\ t}$$

$$0.35 = e^{-0.000019\ t}$$

You bring t (the sample age) down from the exponent by taking the natural logarithm of both sides of the equality:

$$\ln(0.35) = \ln(e^{-0.000019\ t})$$

$$-1.05 = -0.000019 * t$$

$$55{,}000 \text{ years} = t.$$

1) The isotopic abundance and mass of potassium are given below:

| | | |
|---|---|---|
| $^{39}K$ | 93.2581% | 38.964 amu (atomic mass units) |
| $^{40}K$ | 0.0117% | 39.694 amu (atomic mass units) |
| $^{41}K$ | 6.7302% | 40.962 amu (atomic mass units) |

Calculate the mass of 1.0 mol of potassium that contains the average abundance of each of the isotopes.

2) Given that the decay constant for $^{40}K$ is $5.305 * 10^{-10}$ per year, calculate the half-life of $^{40}K$.

3) Parent isotope A decays into daughter product B with a half-life of 109,000 years. If you have an accelerator mass spectrometer that can detect as few as 1 parent isotope per 999 daughters, what is the oldest sample age that you can determine using this method? (**Hint:** Assume that the sample consisted of 100% parent isotope at t=0)

**Numerical Dating**

$$\sigma_{ave} = \left(\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} + \ldots + \frac{1}{\sigma_n^2}\right)^{-0.5}$$

The Earth is perpetu... ace. This high-energy form of radiation creates fre... neutrons interact with nitrogen (the most abundant ... isotope of carbon plus a hydrogen atom:

$$\mu_{ave} = \sqrt{\sigma_{ave}^2 * \left(\frac{\mu_1^2}{\sigma_1^2} + \frac{\mu_2^2}{\sigma_2^2} + \ldots + \frac{\mu_n^2}{\sigma_n^2}\right)} \qquad (4.3)$$

Once created in the upper at... form $CO_2$ gas, which mixes quickly throughout the whole atmosphere.

Of the three isotopesof carbon, only $^{14}C$ is unstable and radioactive. Over time, $^{14}C$ atoms decays back into the $^{14}N$ from which they came:

$$^{14}C \Rightarrow {}^{14}N + \text{electron} + \text{neutrino}. \qquad (4.4)$$

This is another example of *beta decay* (see Figure 4.2). Like all unstable isotopes, $^{14}C$ decays at a uniform rate; its half-life is 5730 years.

All organisms incorporate carbon from the atmosphere into their bodies – plants directly from photosynthesis and vegetarians and carnivores by ingesting other plants or animals. So long as an organism is alive, it contains the same proportion of unstable $^{14}C$ to stable $^{12}C$ as the atmosphere, or as the ocean if the organism lives there. When an organism dies, however, it stops interacting with the atmosphere or ocean, and the proportion of $^{14}C$ in its body begins to decline as a result of radioactive decay.

When a geologist or an archeologist unearths a fragment of bone, wood, charcoal, shell, etc., they can analyze the ratio of $^{14}C$ to $^{12}C$ in the sample to determine how long ago the organism died. Two laboratory methods are used to measure this ratio. In the first method, scientists measure the number of radioactive decays in a carbon sample. For example, in 1.0 grams of *modern* carbon, 13.56 $^{14}C$ atoms (on average) turn into $^{14}N$ each minute (13.56 decays per minute, or *dcm)*. In 1.0 g of 5730 year-old carbon, only one-half of the original $^{14}C$ remains, and only 6.78 radioactive decays would be measured. Using this technique, the age of samples as old as about 40,000 years can be determined. In the second laboratory method, scientists use an Accelerator Mass Spectrometer (AMS) to measure directly the proportion of $^{14}C$ atoms versus the lighter $^{12}C$ atoms. Using this second technique, samples as old as 70,000 years can be analyzed, and only very small quantities of carbon are required.

Radiocarbon ages are reported as a mean value ($\mu$) and associated measurement uncertainty ($\sigma$), for example 5320±170 yBP (years before present). The uncertainty traditionally is reported as a *one standard deviation* range, meaning that there is a 68% likelihood that that actual sample age falls within that range and a 95% likelihood that it will fall within double that range. In the example of a reported age of 5320±170 years, this means that there is a 68% likelihood that the actual age is between 5150 and 5490 years BP and a 95% likelihood that the age is between 4980 and 5660 years BP. As with all r c results, more than one analysis of the same sample or deposit is always desirable. Multiple age estimates cannot simply be averaged, however. The method for combining multiple mean-and-standard-deviation estimates ($\mu_1 \pm \sigma_1$, $\mu_2 \pm \sigma_2$, ..., $\mu_n \pm \sigma_n$) is:

(4.5)

(4.6)

The new, properly combined age would be $\mu_{ave} \pm \sigma_{ave}$. For example, two age estimates of 970±60 ($\mu_1$=970; $\sigma_1$=60) and 1020±100 ($\mu_2$=1020; $\sigma_2$=100) would be combined into 983±51 years BP ($\mu_{ave}$=983; $\sigma_{ave}$=51). Note that the combined mean age of 983 years falls between the two sample means (closer to 970 because the uncertainty of that result is small). Also, the combined standard deviation of 51 years is smaller than either of the two original uncertainties because more data usually serves to reduce uncertainty.

Example 4.3.

Example 4.2 discussed a theoretical isotope (isotope A) with a half-life of 55,000 years (k = 0.000019). You are now given the additional information that a modern 1.0 g sample of the isotope emits 4.86 decays per minute (dcm). If a 3.0 g sample of isotope A and its stable daughter product now emits 9.72 dcm, what is the age of the sample?

The key to solving this problem is that the radioactivity (dcm) of a sample is directly proportional to the amount of parent isotope present (so long as the parent is the sole source of radioactivity). If 1.0 g of modern isotope A emit 4.86 dcm, then a 1.0 g sample that is 37,000 years (one half-life) old will emit 2.43 dcm. Since radioactive emissions are directly proportional to the number of parent atoms present, then you can use that value in place of N and $N_o$ in Equation 4.1, so long as you correct for sample weight.

If a 1.0 g sample of modern isotope A emits 4.86 dcm, then a 3.0 g sample would emit:

$$(3.0 \div 1.0) * 4.86 \text{ dcm} = 14.58 \text{ dcm}.$$

Using Equation 4.1:

$$9.72 \text{ dcm} = 14.58 \text{ dcm} * e^{-0.000019\ t}$$

Solving for t (age of the sample) using the steps outlined in Example 4.2:

$$t = 21{,}000 \text{ years.}$$

1) Calculate the rate constant, k, for the decay of $^{14}C$ in years.

## Numerical Dating

2) You analyze a 6.5 g sample of carbon and find that it emits 2.3 beta particles per minute (dcm). What is the age of this carbon sample. (Remember that 1.0 g of modern $^{14}C$ emits 13.56 dcm)

Sample age = __________

3) A 5730 year-old, 1.0 g sample consists of 90% original carbon and 10% modern carbon. If you analyze the $^{14}C$ in this sample, what will be its apparent age? In other words, if you analyzed the sample without knowing about the contamination, what age would you get? The problem is begun for you below:

0.9 g 5730 yr carbon = _____ dcm

0.1 g modern carbon = _____ dcm

1.0 g Total Sample = _____ dcm

Actual age = _ 5730 yrs _

Apparent age = __________

4) A 34,380 yr old sample consists of 90% original carbon and 10% modern carbo If you analyze the $^{14}C$ in this sample, what will be its apparent age?

Actual age = _ 34,380 yrs

Apparent age = __________

5) Using your results from Questions 3 and 4 above, how does sample age affect the potential for contamination in radiocarbon analysis?

6) The following age estimates are the results radiocarbon analyses, dating the age of a large earthquake on the San Andreas fault (the dates are from the Pallett Creek trench, which is the subject of Exercise 9; Sieh et al, 1989). Using Equations 4.5 and 4.6, find the combined mean and standard deviation of these radiocarbon age estimates. Also, state the age range during which you are 95% certain the earthquake *actually* occurred.

1211 ± 58 yBP
1227 ± 16 yBP
1215 ± 17 yBP
1223 ± 16 yBP

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